

# THE BIMODAL GALAXY COLOR DISTRIBUTION: DEPENDENCE ON LUMINOSITY AND ENVIRONMENT

MICHAEL L. BALOGH,<sup>1,2</sup> IVAN K. BALDRY,<sup>3</sup> ROBERT NICHOL,<sup>4</sup> CHRIS MILLER,<sup>4</sup> RICHARD BOWER<sup>2</sup> & KARL GLAZEBROOK<sup>3</sup>

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## ABSTRACT

We analyse the  $u-r$  color distribution of 24346 galaxies with  $M_r \leq -18$  and  $z < 0.08$ , drawn from the Sloan Digital Sky Survey first data release, as a function of luminosity and environment. The color distribution is well fit with two Gaussian distributions, which we use to divide the sample into a blue and red population. At fixed luminosity, the mean color of the blue (red) distribution is nearly independent of environment, with a weakly significant ( $\sim 3\sigma$ ) detection of a trend for colors to become redder by 0.1–0.14 (0.03–0.06) mag with a factor  $\sim 100$  increase in local density, as characterised by the surface density of galaxies within a  $\pm 1000 \text{ km s}^{-1}$  redshift slice. In contrast, at fixed luminosity the fraction of galaxies in the red distribution is a strong function of local density, increasing from  $\sim 10$ –30 per cent of the population in the lowest density environments, to  $\sim 70$  per cent at the highest densities. The strength of this trend is similar for both the brightest ( $-23 < M_r < -22$ ) and faintest ( $-19 < M_r < -18$ ) galaxies in our sample. The fraction of red galaxies within the virialised regions of clusters shows no significant dependence on velocity dispersion. Even at the lowest densities explored, a substantial population of red galaxies exists, which might be fossil groups. We propose that most star-forming galaxies today evolve at a rate that is determined primarily by their intrinsic properties, and independent of their environment. Any environmentally triggered transformations from blue to red colors must either occur on a short timescale, or preferentially at high redshift, to preserve the simple Gaussian nature of the color distribution. The mechanism must be effective for both bright and faint galaxies.

*Subject headings:* galaxies: clusters — galaxies: evolution

## 1. INTRODUCTION

The local galaxy population is known to consist broadly of two types, identifiable for example by their morphological properties, and are termed late-type (spiral) and early-type (E/S0) galaxies. Recently, this division has been quantified in large datasets, in the related quantities of broadband color (Strateva et al. 2001; Blanton et al. 2003a; Kauffmann et al. 2003) and star formation rate (SFR, Brinchmann et al. 2003; Balogh et al. 2004, hereafter Paper II). In particular, the color distribution at fixed luminosity is surprisingly well modelled by only two Gaussian distributions (Baldry et al. 2004, hereafter Paper I). The mean and variance of these two distributions are strong functions of luminosity, or stellar mass (see also Bernardi et al. 2003a; Blanton et al. 2003a; Hogg et al. 2004); a similar trend is seen out to  $z \sim 1$  (Bell et al. 2004).

Dressler (1980) was first to show that the fraction of late-type galaxies depends strongly on local galaxy environment, and related trends in SFR have also been observed (e.g. Paper II, Miller et al. 2003). If these trends are due to an environmentally-induced transformation, we can look for clues to its nature in the change of the properties of galaxies within each type as a function of environment. For example, if the transformation is due to a decreasing SFR in late-type (blue) galaxies due to interactions with neighbouring galaxies, then their color distribution should be skewed toward redder colors in denser environments.

Many studies of the fundamental plane have shown that the

properties of early-type galaxies are nearly independent of environment (e.g. Dressler et al. 1987; Bernardi et al. 2003b). The properties of the blue population as a function of environment have been studied in less detail; early suggestions that their colors do not depend on environment were seen in the small sample of Larson et al. (1980). This result has been supported by analysis of the Tully–Fisher relation in clusters, groups and the field, using samples of several hundred galaxies. In particular, the scatter in this relation is related to galaxy color, and it has been shown to be insensitive to environment (e.g. Giuricin et al. 1986; Biviano et al. 1990).

Using galaxy colors to describe the galaxy population, rather than morphological types, has the advantage that they are easily quantifiable, the measurements are robustly reproducible, and models exist which allow us to directly relate them to star formation histories with minimal assumptions (e.g. Bruzual & Charlot 2003). In particular, in Paper I we have fit the color distributions of galaxies selected from the Sloan Digital Sky Survey (SDSS, York et al. 2000) with a two-component Gaussian model, as a function of luminosity. This technique has an advantage relative to using strict color cuts to define separate populations (e.g. Butcher & Oemler 1984; Kodama & Bower 2001), as it accommodates photometric and astrophysical uncertainties, such as aperture effects (Bernardi et al. 2003c), dust reddening and stochastic variations in star-formation history. Furthermore, no a priori assumption about how to classify the population is required.

In Paper I we used this novel procedure to show that the luminosity function of red galaxies is consistent with a model in which they are built up from mergers of blue galaxies. In this *Letter*, we develop this investigation by exploring how the model fits depend on local environment.

## 2. DATA

To allow us to reliably measure local galaxy densities, we select a sample of galaxies from the first data release of the

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<sup>1</sup> Department of Physics, University of Waterloo, Waterloo, Canada N2L 3G1 E-mail: mbalogh@uwaterloo.ca

<sup>2</sup> Department of Physics, University of Durham, South Road, Durham DH1 3LE, UK Email: r.g.bower@durham.ac.uk

<sup>3</sup> Department of Physics and Astronomy, Johns Hopkins University, 3400 North Charles Street, Baltimore, MD 21218-2686 USA. Email: baldry.kgb@pha.jhu.edu

<sup>4</sup> Department of Physics, Carnegie Mellon University, 5000 Forbes Avenue, Pittsburgh, PA 15213 Email: nichol,chrism@cmu.edu

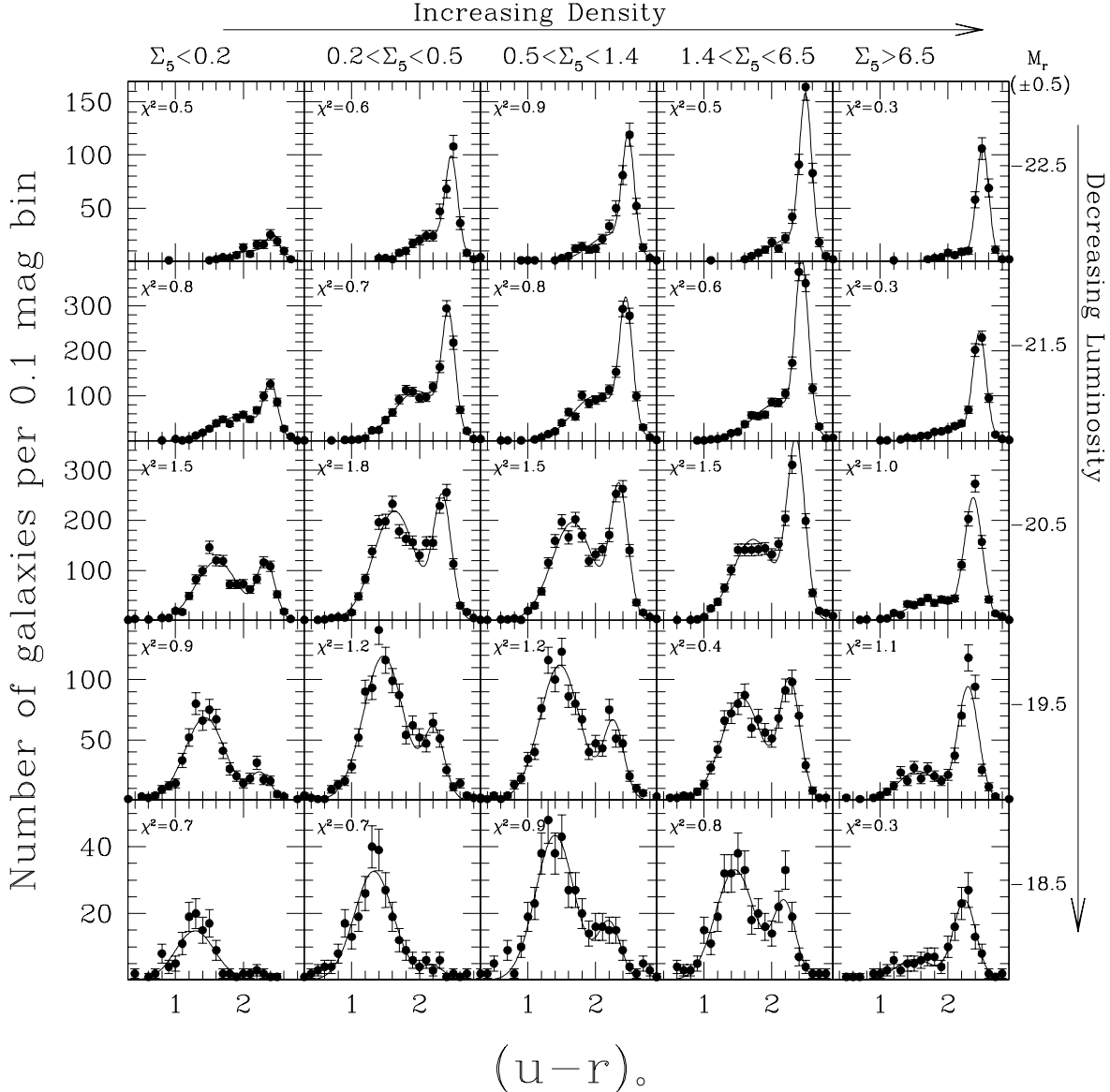


FIG. 1.— The *solid points* in each panel show the galaxy color distribution for the indicated 1 magnitude range of luminosity (right axis) and the range of local projected density, in  $\text{Mpc}^{-2}$ , shown on the top axis.  $1\text{-}\sigma$  error bars are given by  $\sqrt{N+2}$ , where  $N$  is the number of galaxies in each bin. The *solid line* is a double Gaussian model, with the dispersion of each distribution a function of luminosity only. The reduced  $\chi^2$  value of the fit is shown in each panel.

SDSS (Abazajian et al. 2003), in the redshift range  $z < 0.08$ , with luminosities  $M_r < -18$ , assuming a  $\Lambda\text{CDM}$  cosmology with  $\Omega_m = 0.3$ ,  $\Lambda = 0.7$  and  $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ . Galaxy colors are measured from model magnitudes (Stoughton et al. 2002), corrected for Galactic extinction using the dust maps of Schlegel et al. (1998) and k-corrected to  $z = 0$  using the Blanton et al. (2003b) model. Projected local densities,  $\Sigma_5$ , are computed from the distance to the fifth nearest neighbour that is brighter than  $M_r = -20$  and within a redshift slice  $\pm 1000 \text{ km s}^{-1}$  of each galaxy, as described in Paper II. Applying this bright limit to the density calculation gives us a uniform density estimate that is applicable to our magnitude limited sample over the full redshift range. To ensure robust measurements, we only consider galaxies sufficiently far from the survey boundary that the density estimate is unbiased, which limits our sample to 24346 galaxies. As a measurement of the

environment on large scales, we use the C4 catalogue, based on the SDSS (Gomez et al. 2003, Miller et al. in prep), to identify galaxies that lie in groups or clusters. Cluster members are defined to be those within the virial radius and within  $1000 \text{ km s}^{-1}$  of the average cluster redshift.

### 3. RESULTS

Figure 1 shows the  $u-r$  color distribution of galaxies in bins of local density and luminosity. The population is divided into five density bins with the three middle bins having an equal number of galaxies and the least and most dense having half as many, to sample the extremes of the distribution. The median density of galaxies in the sample is  $\Sigma_5 \sim 0.8 \text{ Mpc}^{-2}$ ; thus, the lowest density bin (median density  $\sim 0.1 \text{ Mpc}^{-2}$ ) is underdense by a factor  $\sim 8$ , while the densest bin corresponds to the typical density found in cluster cores. Following Pa-

per I, we model the distributions with two Gaussians using a Levenberg-Marquardt algorithm. The mean and amplitude of each distribution are varied as a function of luminosity and local density, while the dispersions are constrained to be a function of luminosity only. The optimal parameters are found by minimizing the  $\chi^2$  fit to the data in Figure 1; these best-fit models are shown as the solid lines.

The most striking result of Figure 1 is that the double-Gaussian model provides an acceptably good fit to all the distributions, with reduced  $\chi^2 \sim 1$ . Specifically, there is no convincing evidence that the shape of the blue distribution is significantly distorted in dense environments as might be expected if these galaxies were slowly being transformed into the late-type (red) population.

The dominant change in the galaxy population as a function of environment is in the relative number of galaxies in each distribution, as seen in earlier morphological (e.g. Dressler 1980) and emission-line (e.g. Paper II) studies. To show this explicitly, we divide the sample into bins of luminosity and environment (either local density or group velocity dispersion) and compute the relative abundance of red galaxies within each bin; the results are shown in Figure 2. There is a strong and continuous dependence on local density, with the fraction of galaxies in the red distribution increasing from 10–30 per cent of the population at the lowest densities, to  $\sim 70$  per cent of the population in the highest density environments. This is stronger than the dependence on luminosity at fixed density; in particular, the trend with density is of a similar magnitude at all luminosities. The fraction of red-distribution galaxies (at fixed luminosity) within the virial radius of clusters is independent of velocity dispersion, within the fairly large uncertainties. This implies that the population differences are primarily related to local galaxy density and not cluster mass or dynamics, in agreement with other work (Dressler 1980; Fairley et al. 2002; De Propris et al. 2004).

In contrast to the strong trend in the fraction of red galaxies with  $\Sigma_5$ , the mean color of each distribution depends only weakly on environment, as shown in Figure 3. Over a factor  $\sim 100$  in density, the mean color of the blue (red) population changes by only 0.1–0.14 (0.03–0.06) mag, depending on luminosity; the strongest trend is in the faint, blue galaxy distribution. These trends are weak, relative to the luminosity dependence: for example, the mean color of the blue population is  $\sim 0.7$  mag redder in the brightest galaxies, compared with the faintest galaxies in the same environment. Similarly, we see little evidence that the dispersion depends on environment: the reduced  $\chi^2$  of the fits do not improve significantly if the dispersions are allowed to vary, and there is no significant trend in the best-fit dispersions with environment.

#### 4. DISCUSSION AND CONCLUSIONS

It has been known for a long time that the galaxy color distribution (and correlated quantities) depends on both environment (e.g. Melnick & Sargent 1977; Butcher & Oemler 1978; Dressler 1980; Mathieu & Spinrad 1981) and luminosity (e.g. de Vaucouleurs 1961; Bower et al. 1992). We have shown here that the two effects are separable if the full color distribution is considered as the sum of two populations: while the mean and dispersion in the color of each type depend strongly on luminosity (Paper I), they are weak functions of environment. For the red galaxy distribution, this is well known (e.g. Sandage & Visvanathan 1978), and is consistent with the idea that these are old galaxies, for which color is only weakly sensitive to the present age (Andreon 2003).

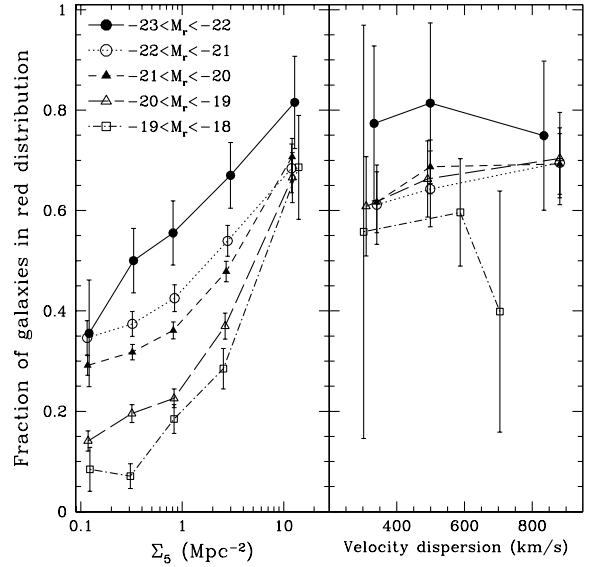


FIG. 2.— The fraction of galaxies in the red distribution, in bins of local density (*left panel*) or cluster velocity dispersion (*right panel*), based on the Gaussian fitting of Fig. 1. Five lines are shown, corresponding to five different luminosity ranges, as indicated. Points are shown with  $1-\sigma$  error bars at the median density or velocity dispersion of each bin. Each point represents the fraction of red galaxies only among galaxies with that luminosity and environment and, therefore, they do not need to add to 100 per cent.

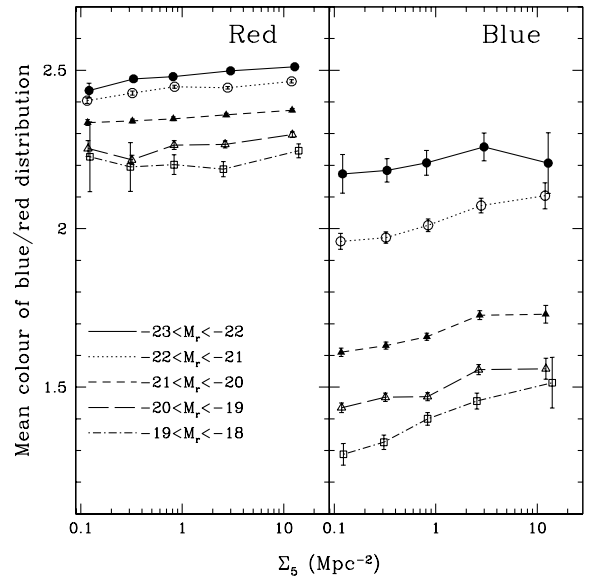


FIG. 3.— The mean color of the red distribution (*left panel*) and the blue distribution (*right panel*) as a function of local density, based on the Gaussian fitting of Fig. 1. Five lines are shown, corresponding to five different luminosity ranges, as indicated. Points with  $1-\sigma$  error bars are shown at the median density of each bin.

However, it is a surprising result that the colors of blue galaxies, which are still actively growing and evolving, show such little dependence on environment, a result that was indirectly revealed through earlier analysis of the Tully–Fisher relation (e.g. Giuricin et al. 1986). For example, if the increased abundance of red galaxies is due to interactions (e.g. mergers and harassment) that increase in frequency monotonically

and smoothly with local galaxy density, we would expect the blue distribution to become increasingly non-Gaussian with density, and to gradually blend into the red distribution. It seems unlikely that the small change of  $\sim 0.1$  magnitudes in the mean color of the blue distribution as a function of environment can be related to the much larger change in the abundance of this population, relative to the red population. Instead, it may indicate a small difference in the recent star formation history, or the distribution of intrinsic properties (e.g. dynamical mass or stellar velocity dispersion) of blue galaxies at fixed luminosity in different environments.

We propose that characteristic properties (e.g. metallicity, dust content, and past-averaged SFR) of the late-type galaxies are determined primarily by their luminosity (likely through its relation to mass or other fundamental, intrinsic quantities) and that only interactions of a certain level trigger a transformation from late to early type. This transformation must be either sufficiently rapid, or sufficiently rare, to keep the overall color distribution unchanged. Furthermore, the mechanism responsible for this transition must be effective for both bright and faint galaxies, as the trends with local density are of a similar magnitude for both populations.

To quantify how rapid this transformation may be, we use the Bruzual & Charlot (2003) stellar population models to follow the color evolution from blue to red, assuming a range of exponential transformation timescales  $\tau$ . We start with a solar-metallicity model of a 9 Gyr old galaxy with a Salpeter (1955) initial mass function, constant SFR, and a two component dust model with an effective extinction of 1 mag, of which 0.3 mag arises from the ambient interstellar medium Charlot & Fall (2000). Brinchmann et al. (2003) have shown that this star formation history is a good description of the local, star forming population. We then assume the red population has been built up by a steady truncation of star formation in blue galaxies, over a Hubble time. If the truncation is rapid ( $\tau < 0.5$  Gyr), the color reddens to  $(u-r)_0 \sim 2.3$  in only 0.75 Gyr. This change is so rapid that we expect only  $\sim 1$  per cent of the total galaxy population to be observed in the mid-transition phase, defined as the  $\sim 0.2$  magnitude dip observed between the two Gaussian distributions. From Figure 1, it is evident that this would amount to an increase of only  $\sim 10$  per cent in these intermediate-color bins, comparable to the observational uncertainties. Therefore, the observed color distribution is not significantly altered by the presence of this transforming population, and the simple Gaussian model remains a good fit to the data.

On the other hand, if the SFR in a blue galaxy decays with an exponential timescale of 2 Gyr, it takes  $\sim 4$  Gyr for

the colors to become as red as the early-type population. In this case, the number of galaxies with intermediate colors at the present day would increase by a factor  $\sim 2$ , and would distort the observed distribution in a way that is inconsistent with the observations. However, we caution that these results are sensitive to the assumption that the transformations occur uniformly in time. If, instead, transitions were more common in the past, the data can accommodate a slower rate of SFR decay, as expected if galaxies are stripped of their hot gas in dense environments (Larson et al. 1980; Balogh et al. 2000).

We therefore conclude that short-timescale transformations could play a role at all densities and luminosities, without disrupting the Gaussian model fit. The small fraction of galaxies predicted to be in the transition phase is comparable to the fraction of spectroscopically identified post-starburst galaxies (Goto et al. 2003a; Quintero et al. 2004), and anemic (passively evolving) spirals (van den Bergh 1976; Goto et al. 2003b) which may be the signature of such transformations (e.g. Dressler & Gunn 1992).

It is interesting to compare these results with the morphology-density relation (Dressler 1980; Postman & Geller 1984). In contrast with the bimodality of the color distribution, there are at least three morphological types that have different dependences on environment: ellipticals, S0s, and spirals. One possibility is that the transforming galaxies correspond to the S0 population, since morphology may change on a longer timescale than color if the change is due to a decline in SFR (Bekki et al. 2002). This interpretation is in qualitative agreement with the dearth of such galaxies at higher redshift (Dressler et al. 1997). More detailed analysis will be the subject of future work, as morphologies for the SDSS galaxies become available (e.g. Kelly & McKay 2004).

Finally, we note that, at all magnitudes, a population of red galaxies exists even in low-density environments; this is consistent with Paper II, where we found a population of galaxies without significant H $\alpha$  emission in all environments. Therefore, either some fraction of the red population must arise independently of environment (e.g., by consumption of the internal gas supply), or these are fossil groups which result from the complete merging of bright galaxies (Ponman et al. 1994; Mulchaey & Zabludoff 1999; Romer et al. 2000).

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